Geomechanical risk assessment for fluid disposal operations

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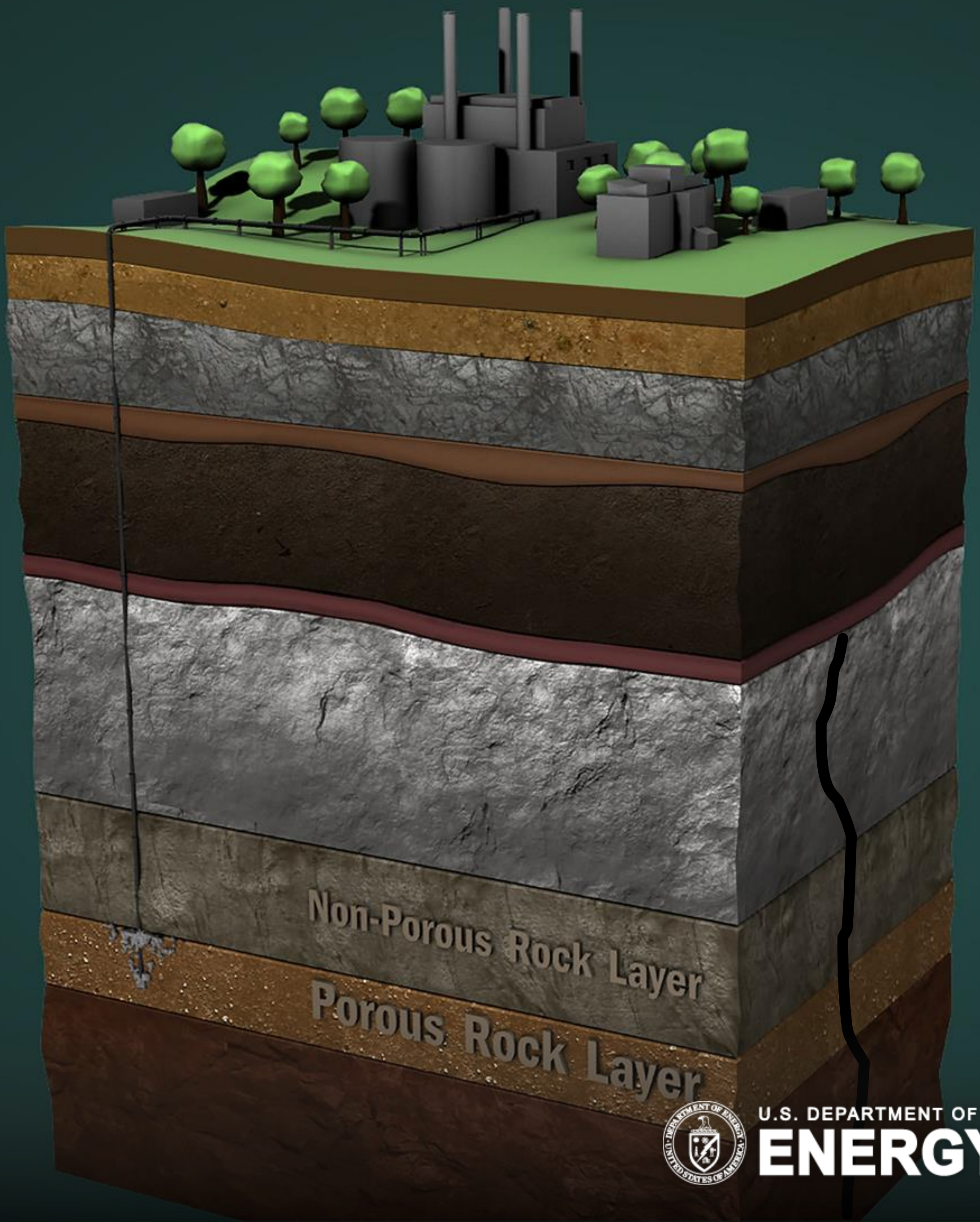

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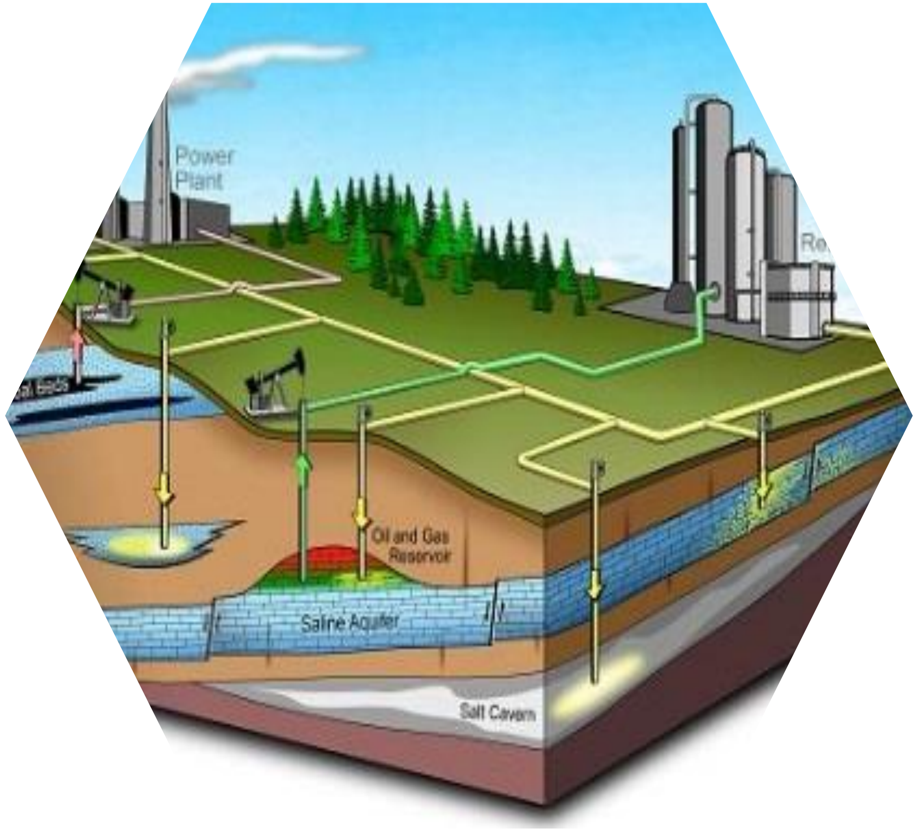
Outline

- **Introduction to geomechanical risks**
- **UQ for subsurface stress estimation**
  - Regional stress observations
  - Core and log data
  - Stress measurements
- **Risk assessment based on stress estimate**
- **Example: SWRP Farnsworth Unit**



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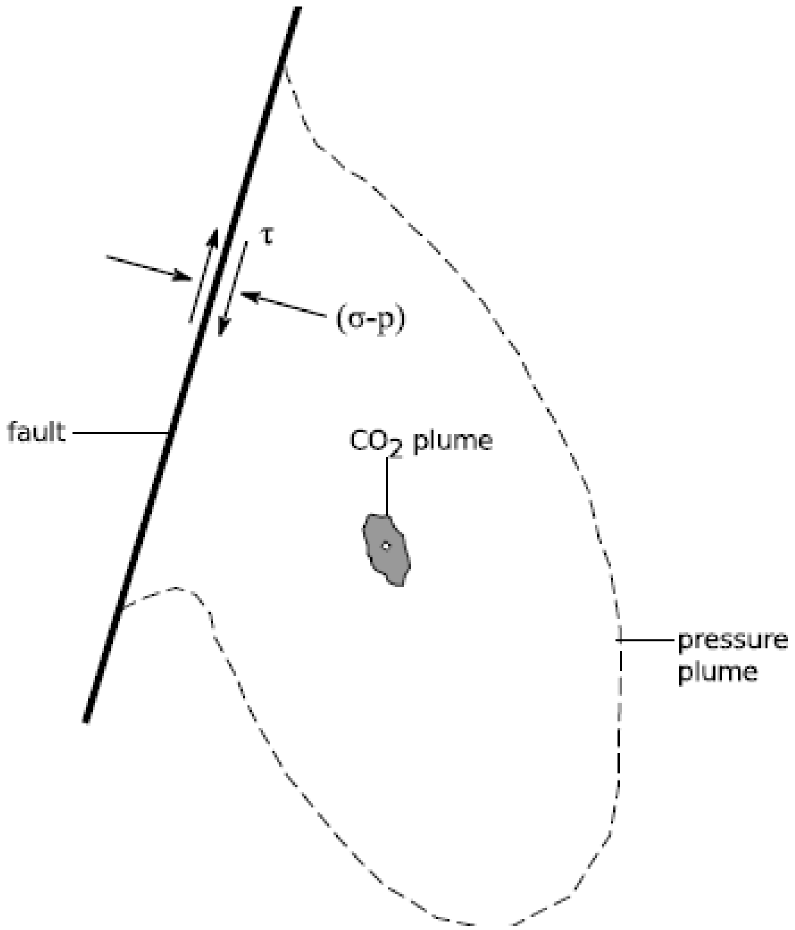
Geomechanical risks: Induced Seismicity

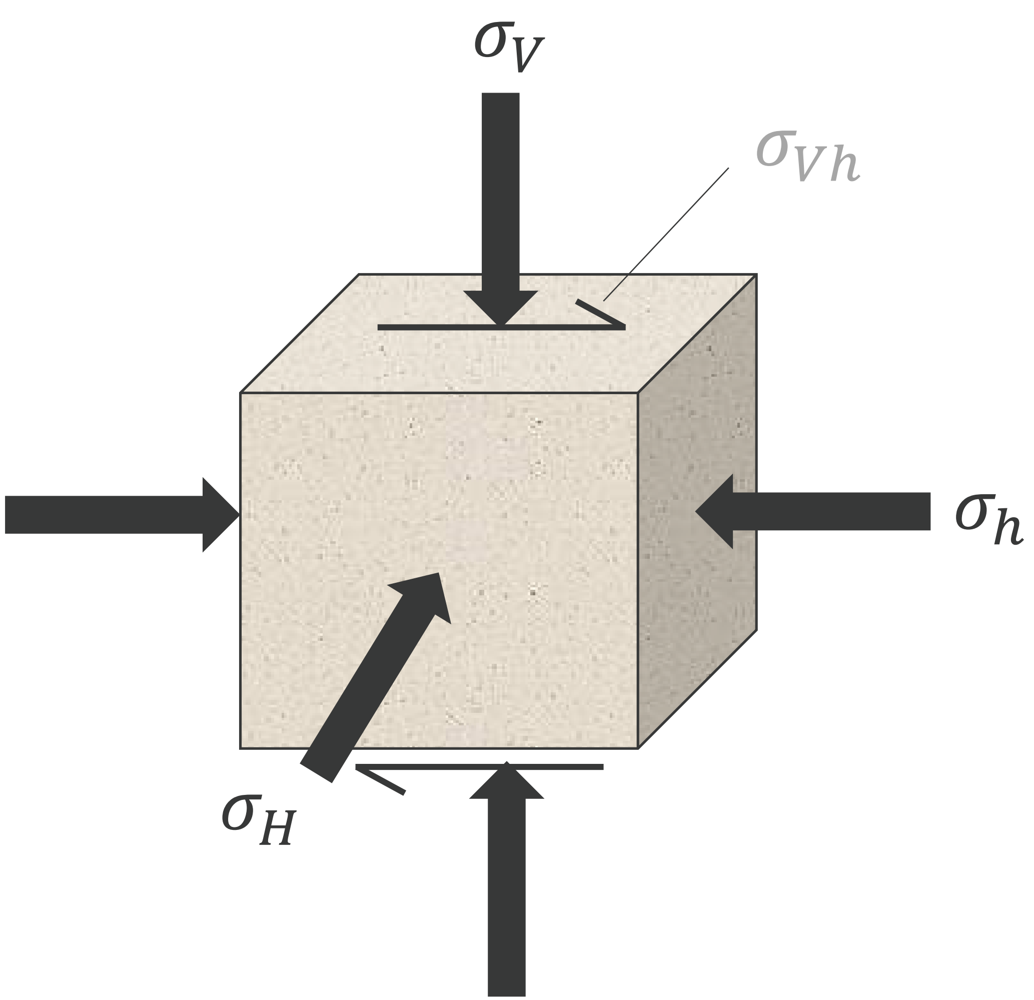


Uncertainties:

- **State of stress**
- **Presence, location, orientation of fault**
- **Magnitude of pore pressure change**
- **Fault properties**

White et al, (2016) Induced Seismicity and Carbon Storage: Risk Assessment and Mitigation Strategies. NRAP-TRS-II-005-2016

Stress tensor has six components



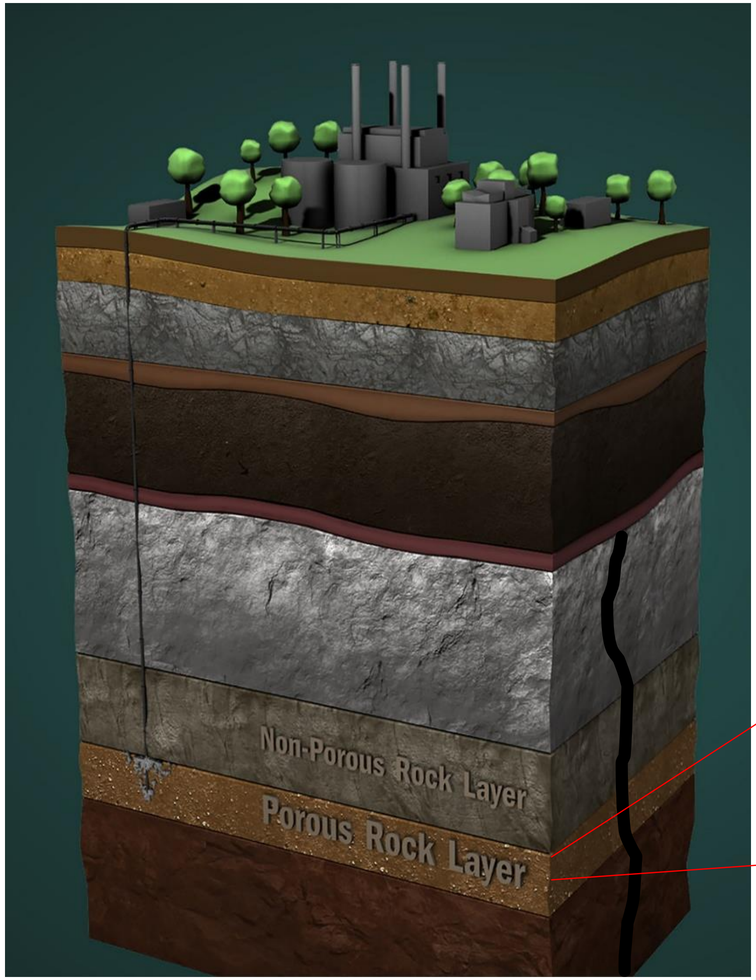
$$\sigma = \begin{pmatrix} \sigma_h & \sigma_{Hh} & \sigma_{Vh} \\ \sigma_{Hh} & \sigma_H & \sigma_{VH} \\ \sigma_{Vh} & \sigma_{VH} & \sigma_V \end{pmatrix}$$

- three principal stresses and three directions

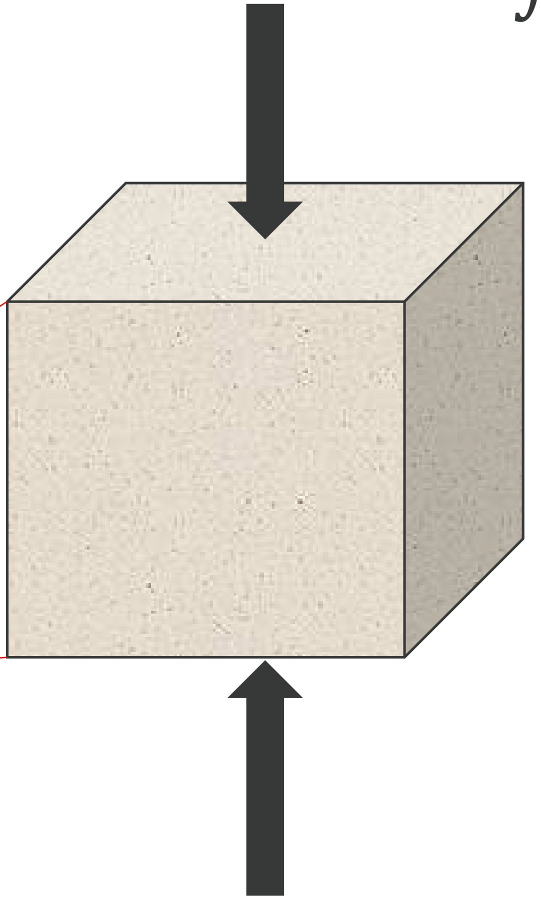
OR

- six components of full tensor

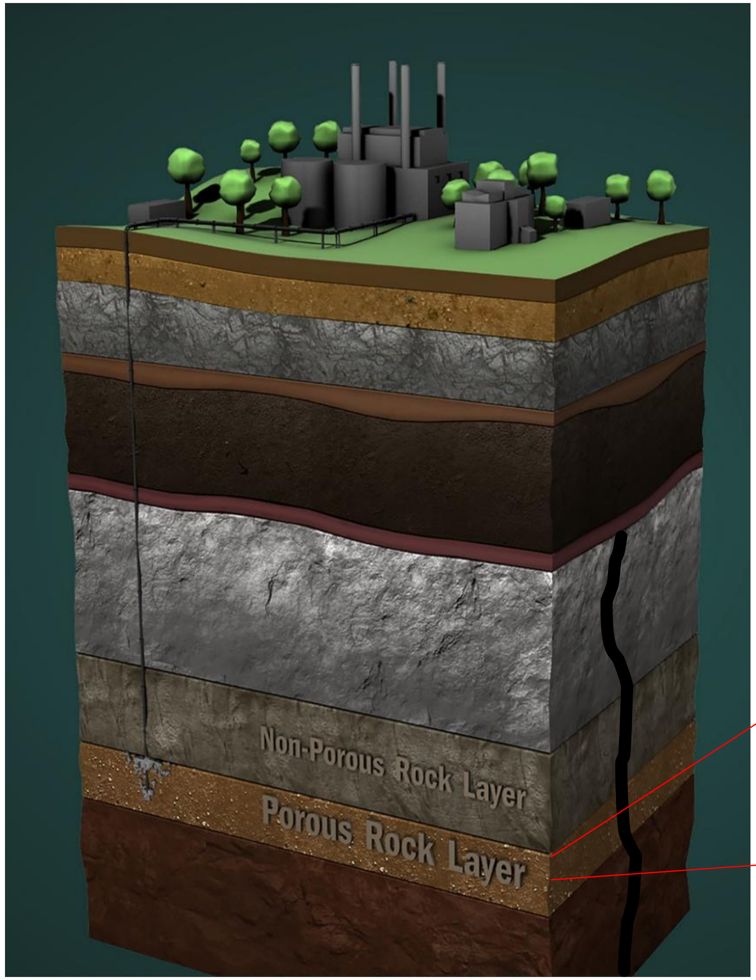
Vertical stress is usually relatively well known

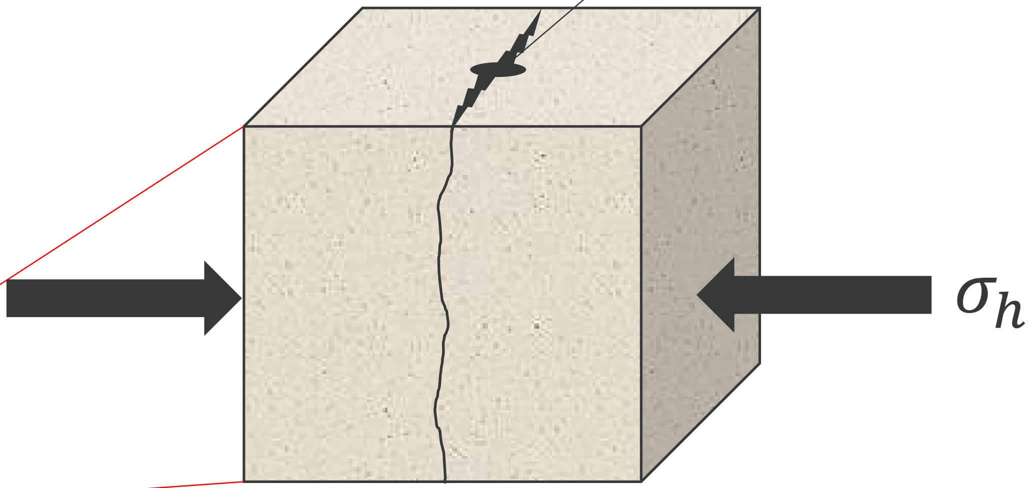


$$\sigma_V(d) \approx \int_0^d \rho_r g z dz$$

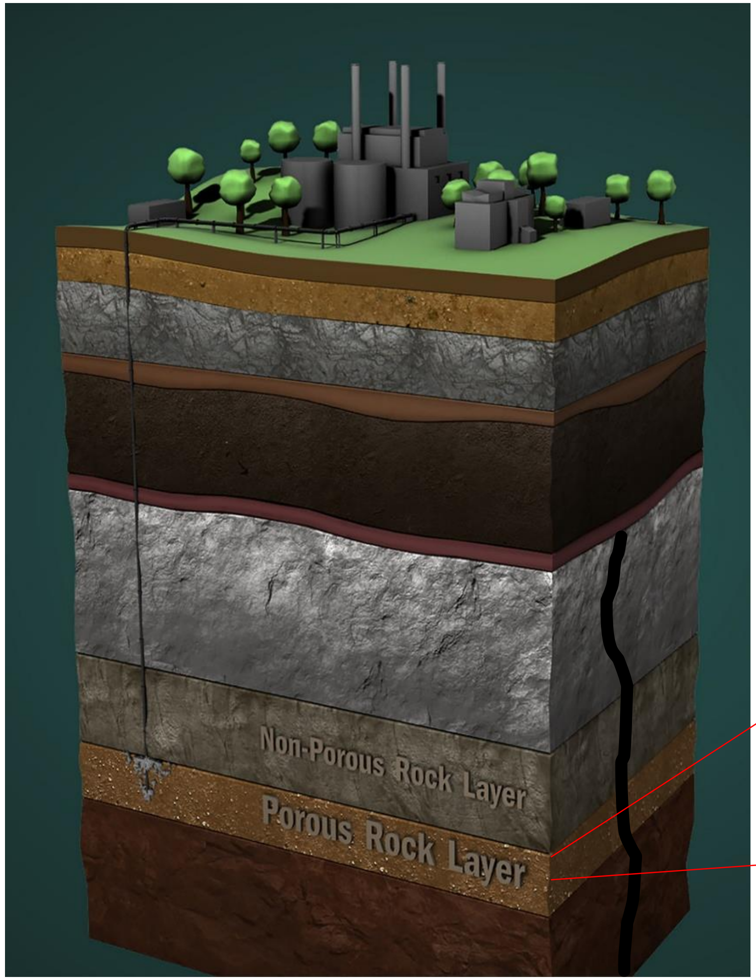


Minimum horizontal stress direction and magnitude needs to be measured

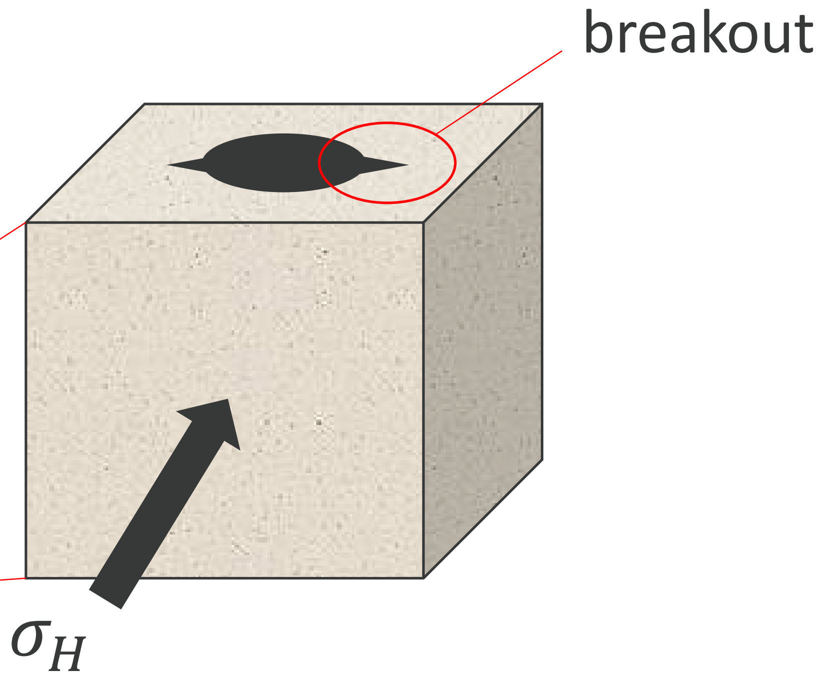




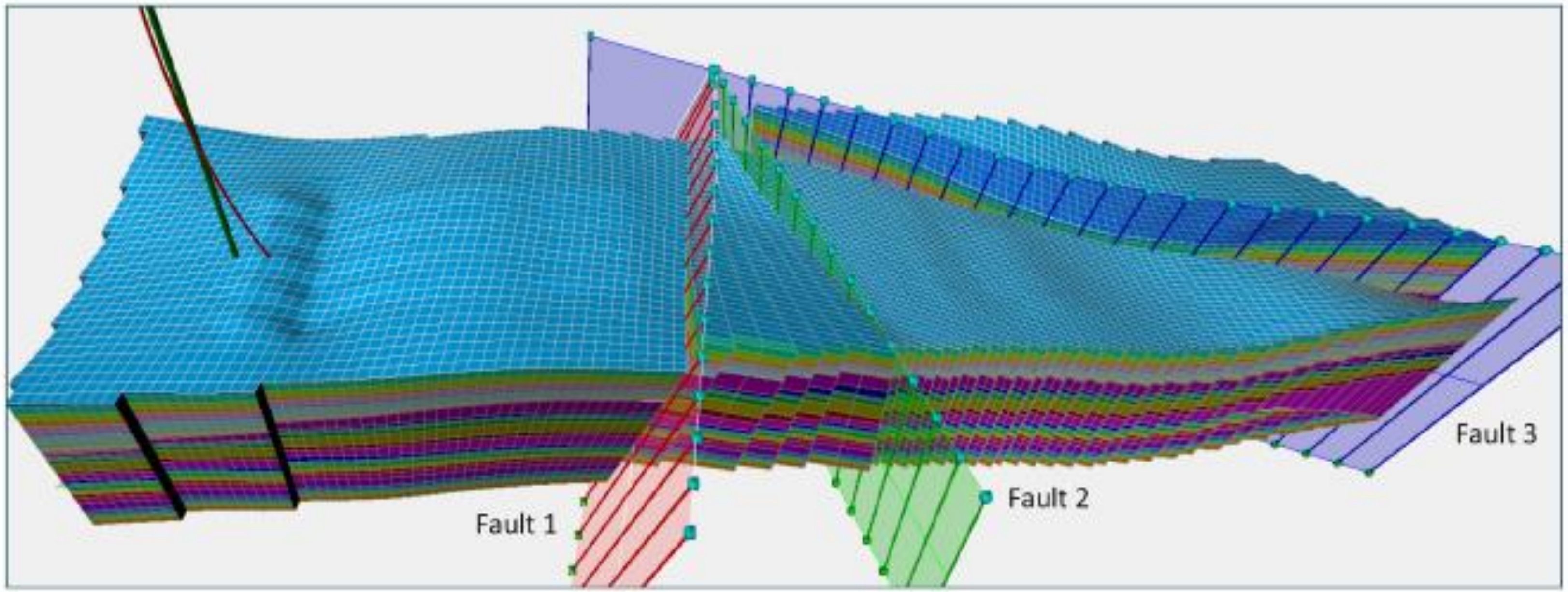
Maximum horizontal stress is difficult to accurately measure



- Wellbore breakouts can indicate $\sigma_H \gg \sigma_h$
- Re-opening fracture with packer can give estimate



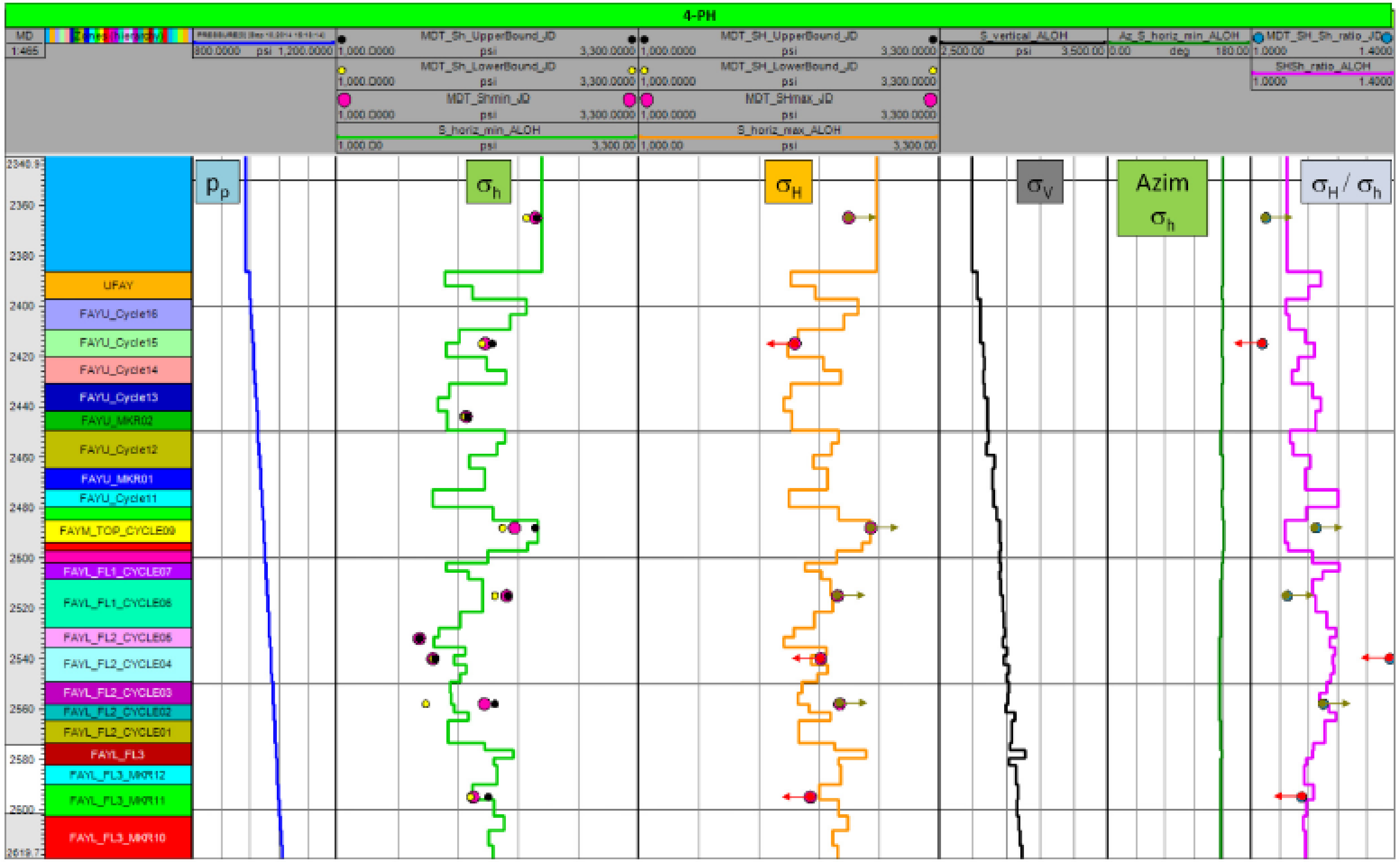
3D geomechanical model requires defining rock mechanical properties to the domain



Example from Bérard, et al, 2015, “High-resolution 3D structural geomechanics modeling for hydraulic fracturing,” SPE-173362-MS

Model calibration with stress measurements

Model is calibrated by specifying tectonic strains to match stress measurements



Estimation is deterministic. It gives no little information about uncertainties.

Example from Bérard, et al, 2015

Sources of stress state uncertainty

- Uncertain rock mechanical properties (in 3D)
- Uncertain boundary conditions/depositional history
- Uncertain stress measurements (or lack thereof!)

Bayesian approach to geomechanical modeling

- **Carefully chosen prior distributions**
  - Stress state/model boundary conditions
  - Rock mechanical properties
- **Express all measurements/observations as statistical distributions**
  - Regional stress observations
  - Mechanical properties measured on core samples
  - Stress measurements
- **Enables a value-of-information analysis to drive further characterization**

Constructing prior distribution for stress state

For this analysis we take σ_V and P_p to be known with high certainty

Begin with uniform (compressive) joint prior distribution:

$$P(\sigma_H) = \begin{cases} \text{const}, \sigma_H > 0 \\ 0, \text{otherwise} \end{cases} \qquad P(\sigma_h) = \begin{cases} \text{const}, \sigma_H > \sigma_h \\ 0, \text{otherwise} \end{cases}$$

Further constraint is provided by strength-based arguments (Zoback et al (2003)):

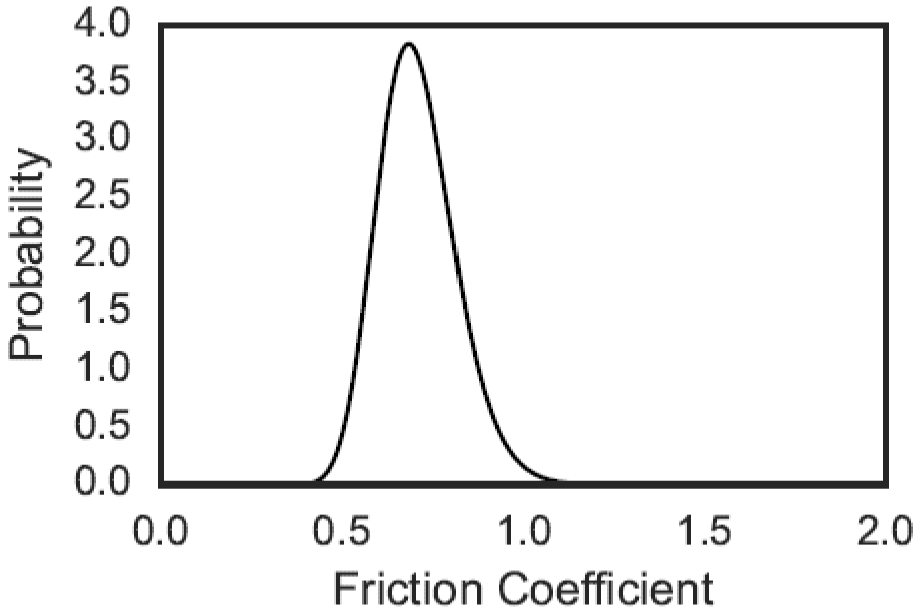
$$P(\sigma_V, \sigma_H, \sigma_h, P_p, \mu_o, C_{of}) = \begin{cases} \text{const}, f_{MC} \leq 0 \\ 0, \mathrm{f}_{MC} > 0 \end{cases}$$

Here $C_{of} = 0$

Mohr-Coulomb or other failure criterion

Stress state constraint by fault strength

Assign lognormal probability distribution for friction coefficient (Steele (2008)) with a mode of 0.68 and $\sigma_\mu = 0.15$



Posterior stress distribution calculated using Bayes' law:

$$P(\sigma_h, \sigma_H | D) = \frac{P(D|\sigma_h, \sigma_H)P(\sigma_h, \sigma_h)}{P(D)}$$

Likelihood function, where D is the existence of faults with the given properties

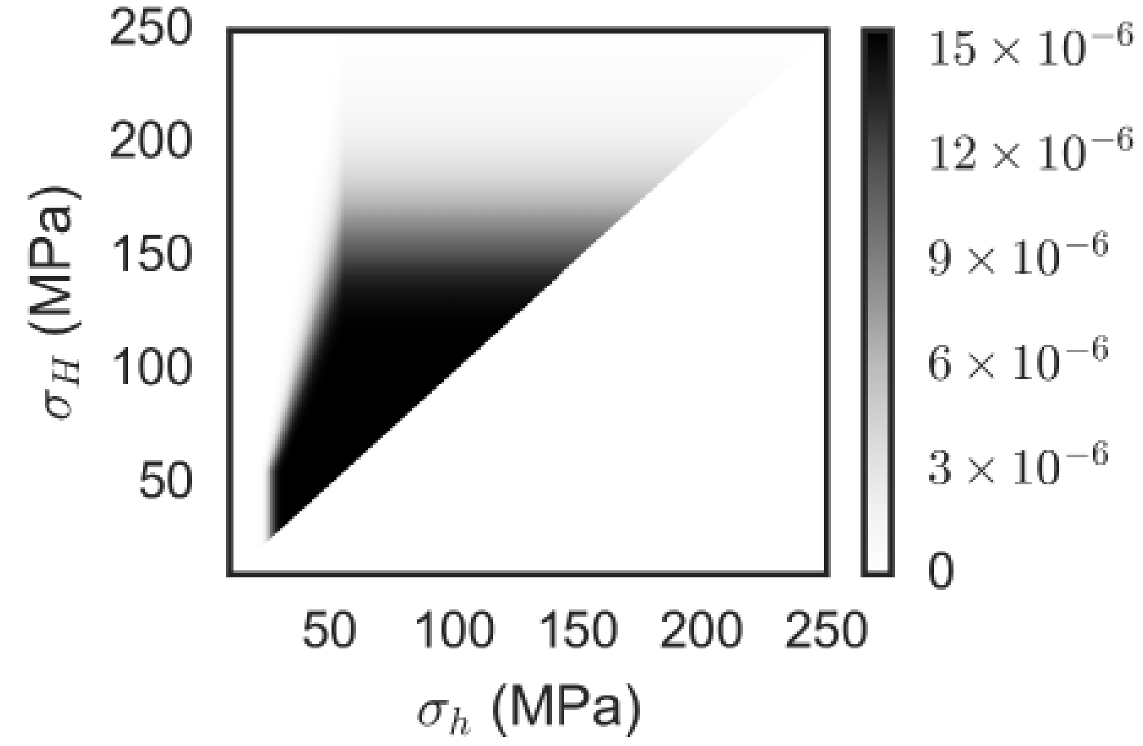
$$P(D|\sigma_H, \sigma_h) = 1 - \frac{1}{2}\mathrm{erfc}\left[-\frac{\ln \mu_c - \mu_o}{\sigma_\mu \sqrt{2}}\right]$$

Stress state constraint by fault strength

Example: In SWRP Farnsworth Unit, the primary reservoir depth is 2344 m

$$\sigma_V = 56 \text{ MPa}$$

$$P_p = 14.8 \text{ MPa}$$



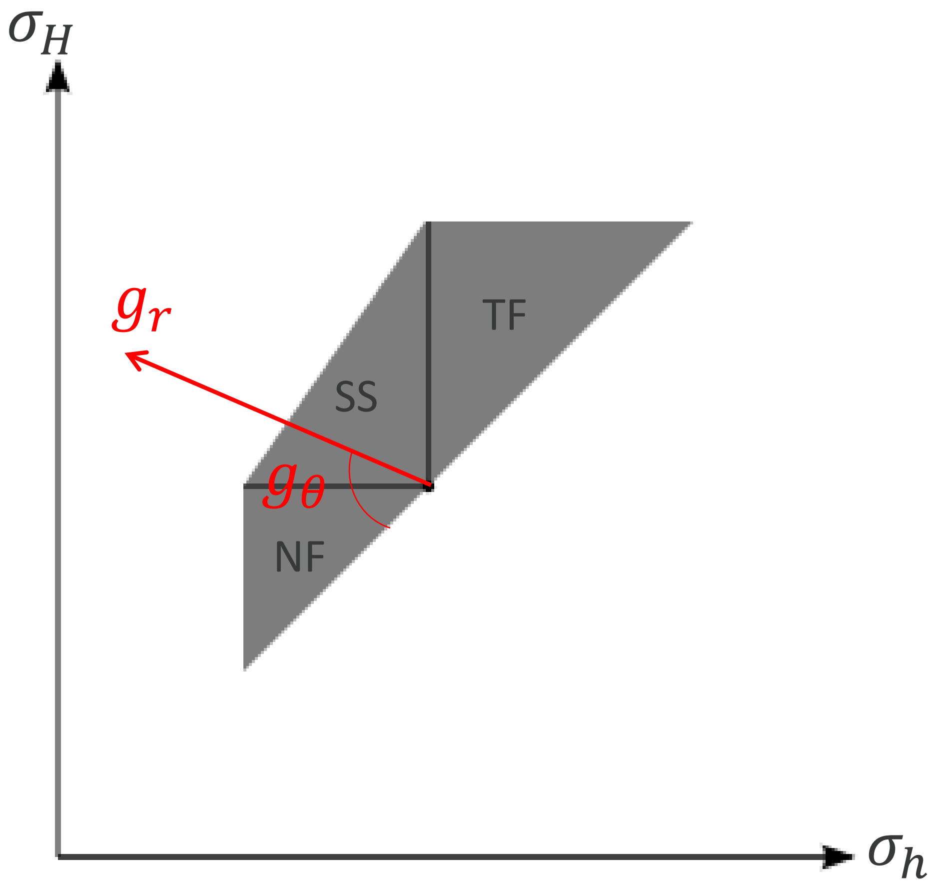
Stress state constraint by regional stress observations

$$g_r = \sqrt{(\sigma_H - \sigma_V)^2 + (\sigma_h - \sigma_v)^2}$$

$$g_\theta = h_o : \hat{h}$$

$$h_o = \frac{1}{\sqrt{2}} \begin{pmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\hat{h} = \frac{1}{g_r} \begin{pmatrix} \sigma_h - \sigma_V & 0 & 0 \\ 0 & \sigma_H - \sigma_V & 0 \\ 0 & 0 & 0 \end{pmatrix}$$



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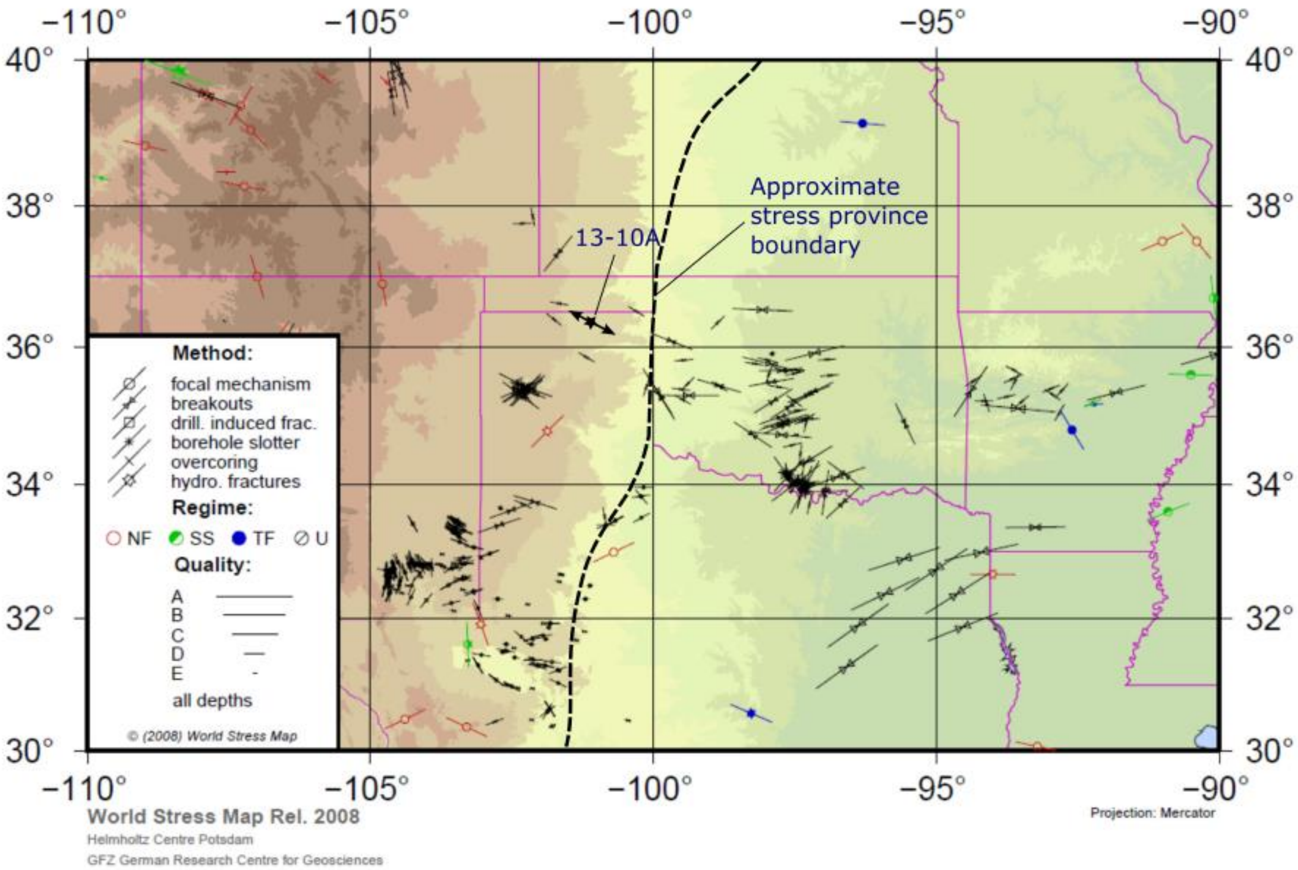
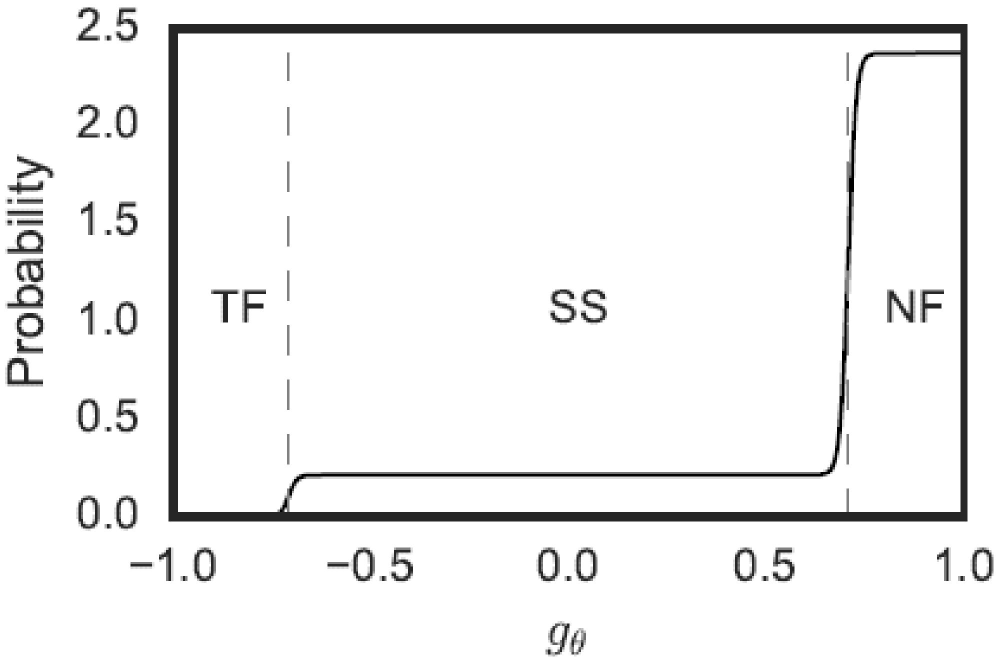
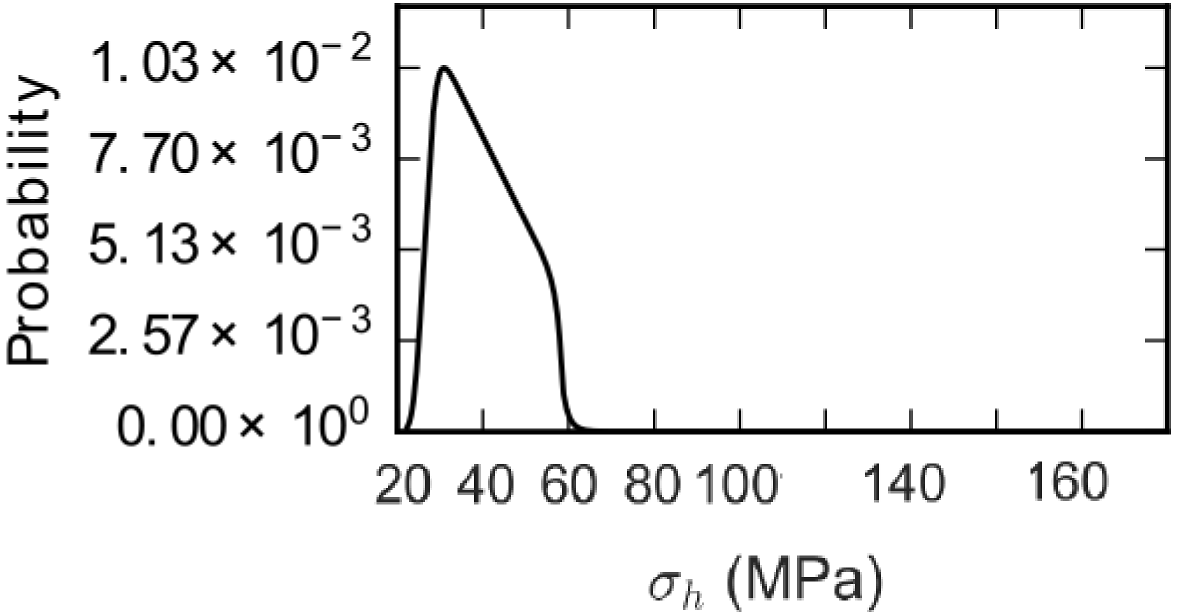
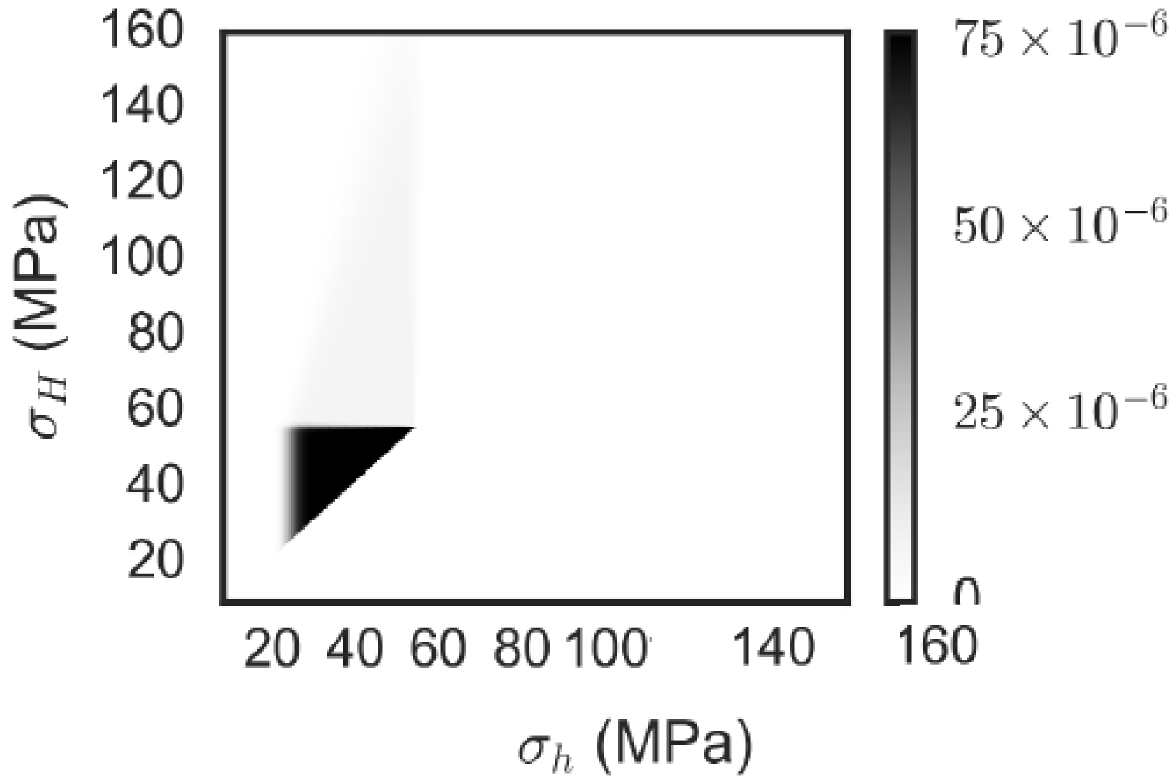


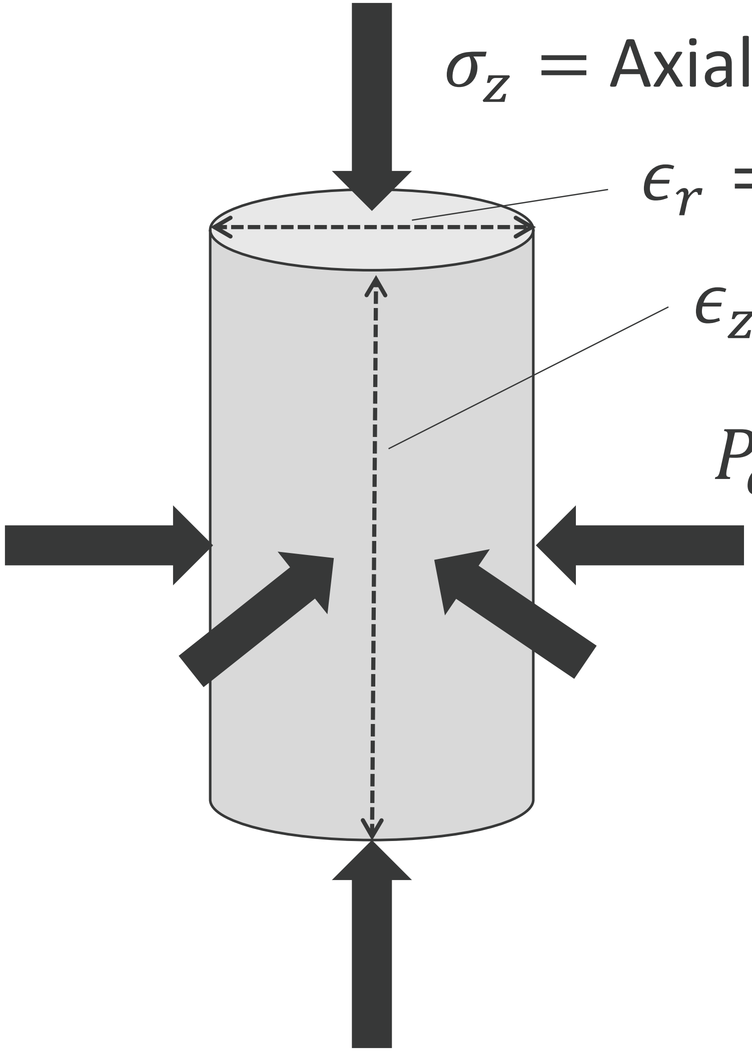


Stress state constraint by regional stress observations





Triaxial compression test



σ_z = Axial stress

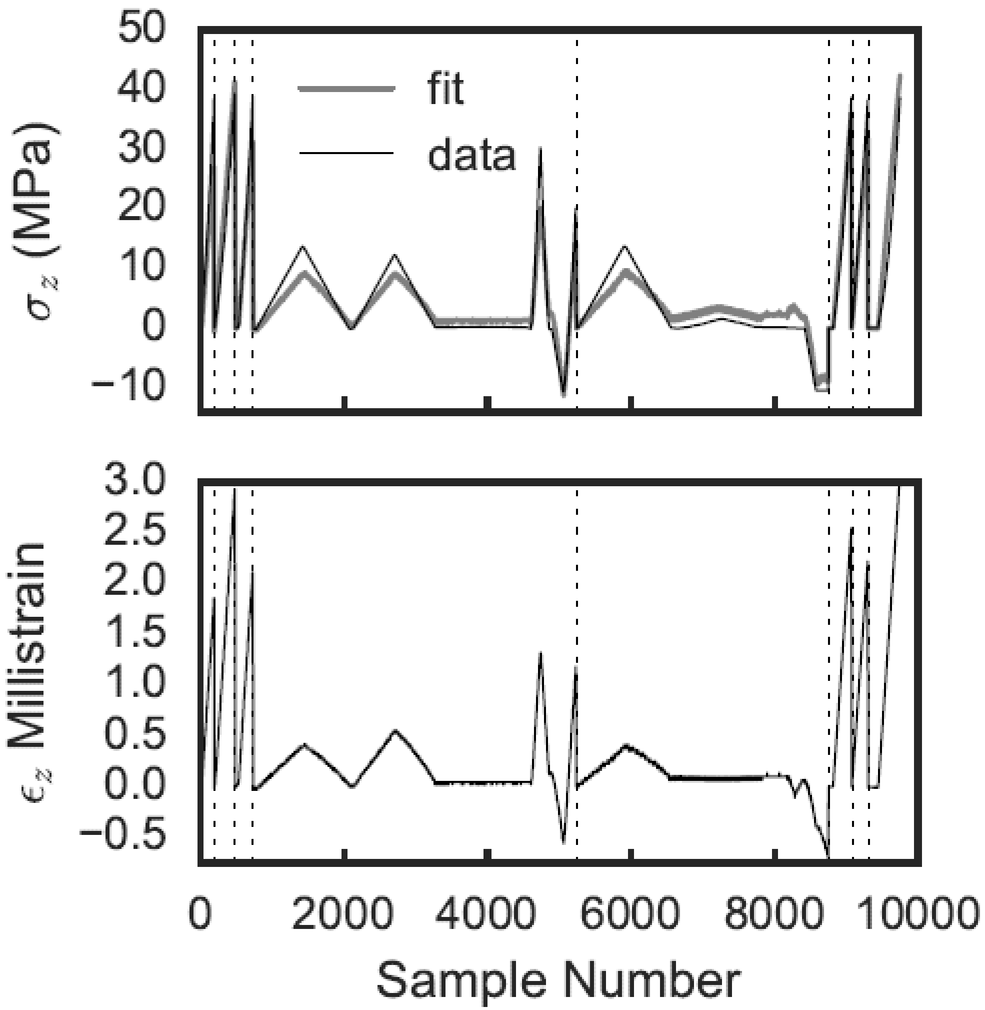
ϵ_r = radial strain

ϵ_z = Axial strain

$P_c = \sigma_x = \sigma_y$ = Radial stress

MCMC analysis of triaxial compression data

Example of axial stress/strain of Morrow SS (SWRP)



Linear elasticity used in this case, where the stress and strain tensors are related by:

$$\sigma_{ij} = C_{ijkl}\epsilon_{kl}$$

Eigenvalues of C_{ijkl} have well defined (lognormal) distributions (Tarantola, 2005).

Objective is to find the joint posterior distribution

$$P(\Lambda_1, \Lambda_2, \Lambda_3, \Lambda_4, \alpha)$$

MCMC analysis of triaxial compression data

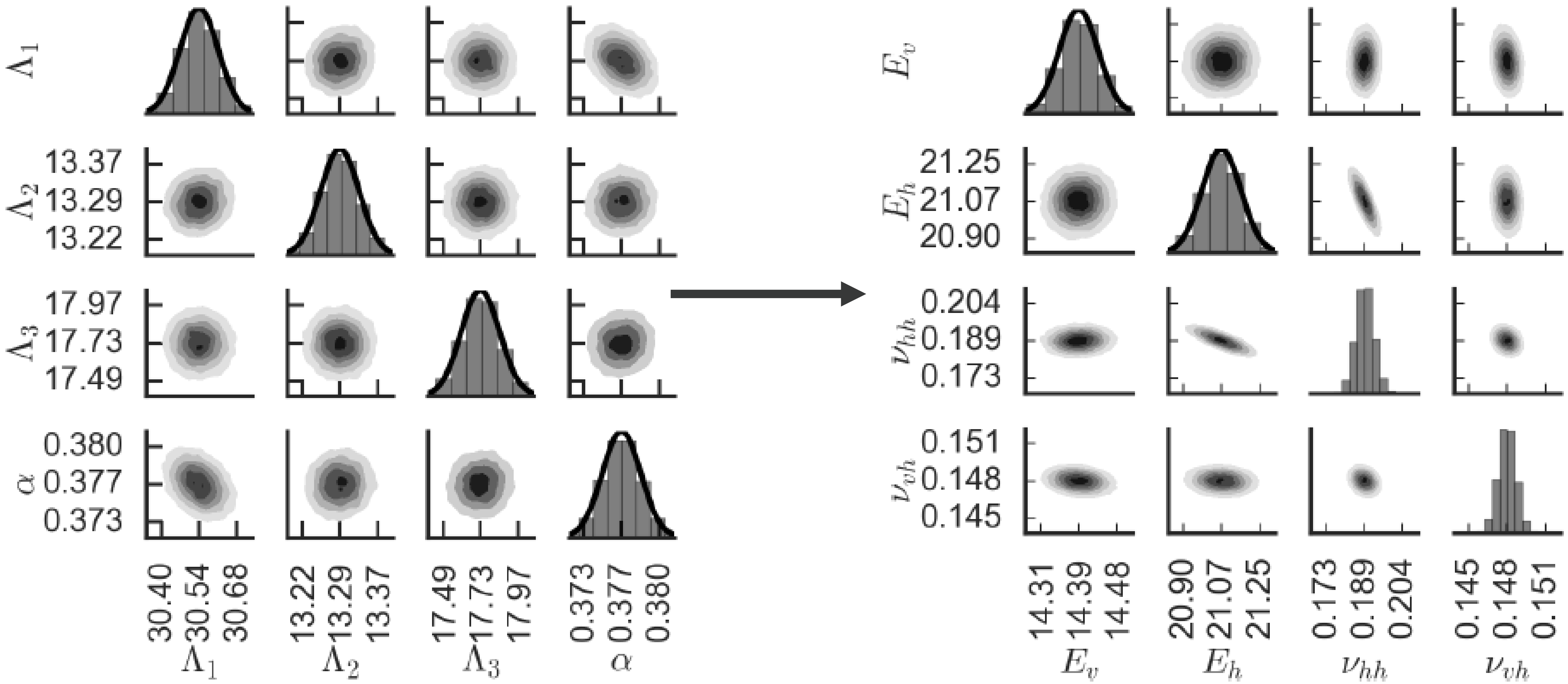
Prior Distributions:

$$P(\log\Lambda_1) = \begin{cases} \text{const}, G_{min} < \Lambda_1 < K_{max} \\ 0, \text{otherwise} \end{cases}$$

$$\nu_{vh} > 0 \rightarrow \; P(\log\Lambda_2) = \begin{cases} \text{const}, \Lambda_1 > \Lambda_2 \\ 0, \text{otherwise} \end{cases}$$

$$\nu_{hh} > 0 \rightarrow P(\log\Lambda_3) = \begin{cases} \text{const}, \Lambda_3 > \dfrac{\Lambda_1\Lambda_2}{\sin^2\alpha(\Lambda_1 - \Lambda_2) + \Lambda_2} \\ 0, \text{otherwise} \end{cases}$$

Example from the Morrow sandstone (SWRP)



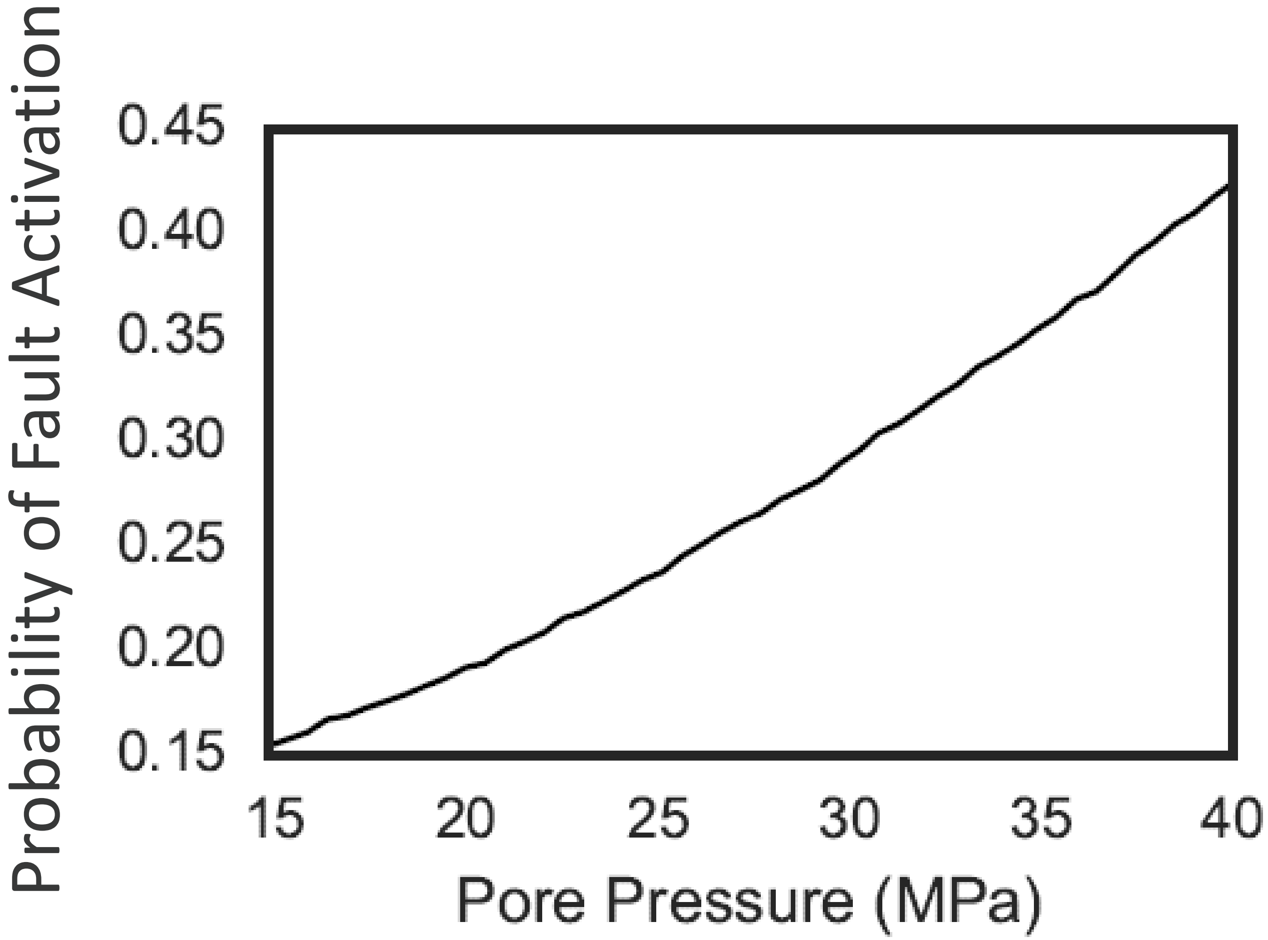
Reservoir stress path using measured elastic properties

Uniaxial strain horizontal stress path:

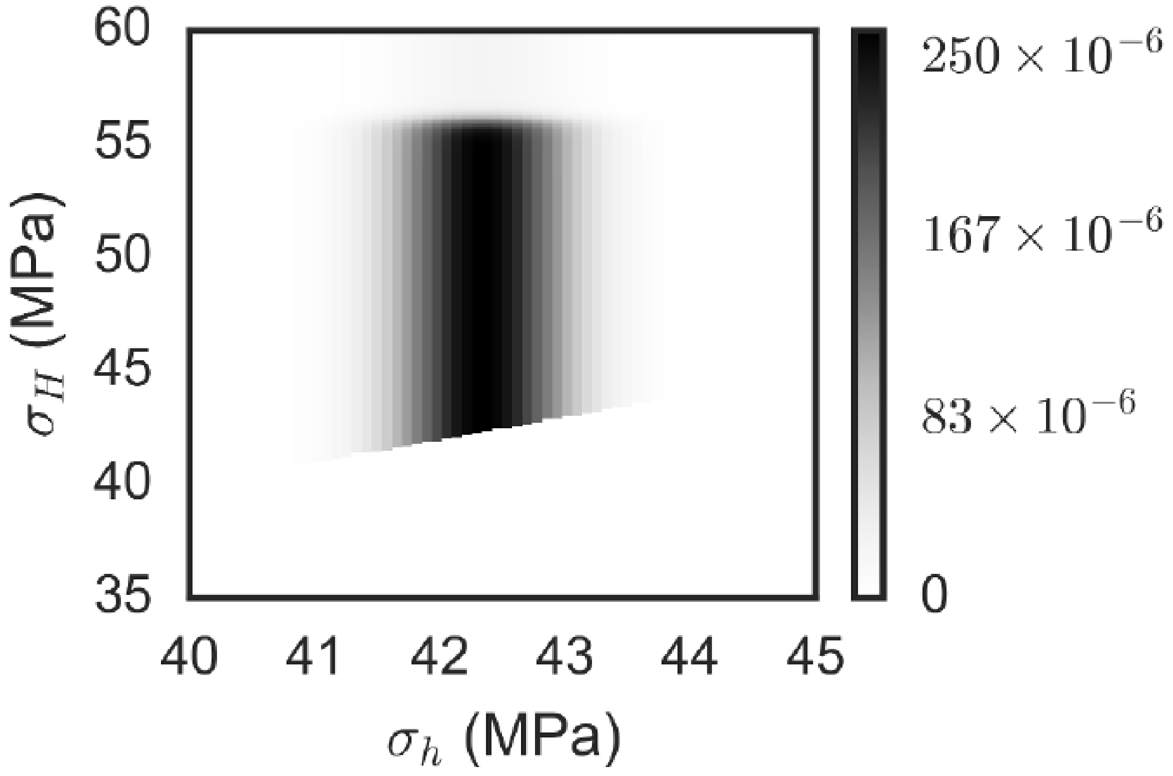
$$\frac{\Delta\sigma_h}{\Delta P_p} = \gamma_h = \alpha_h\left(1 - \frac{C_{13}}{C_{33}}\right)$$

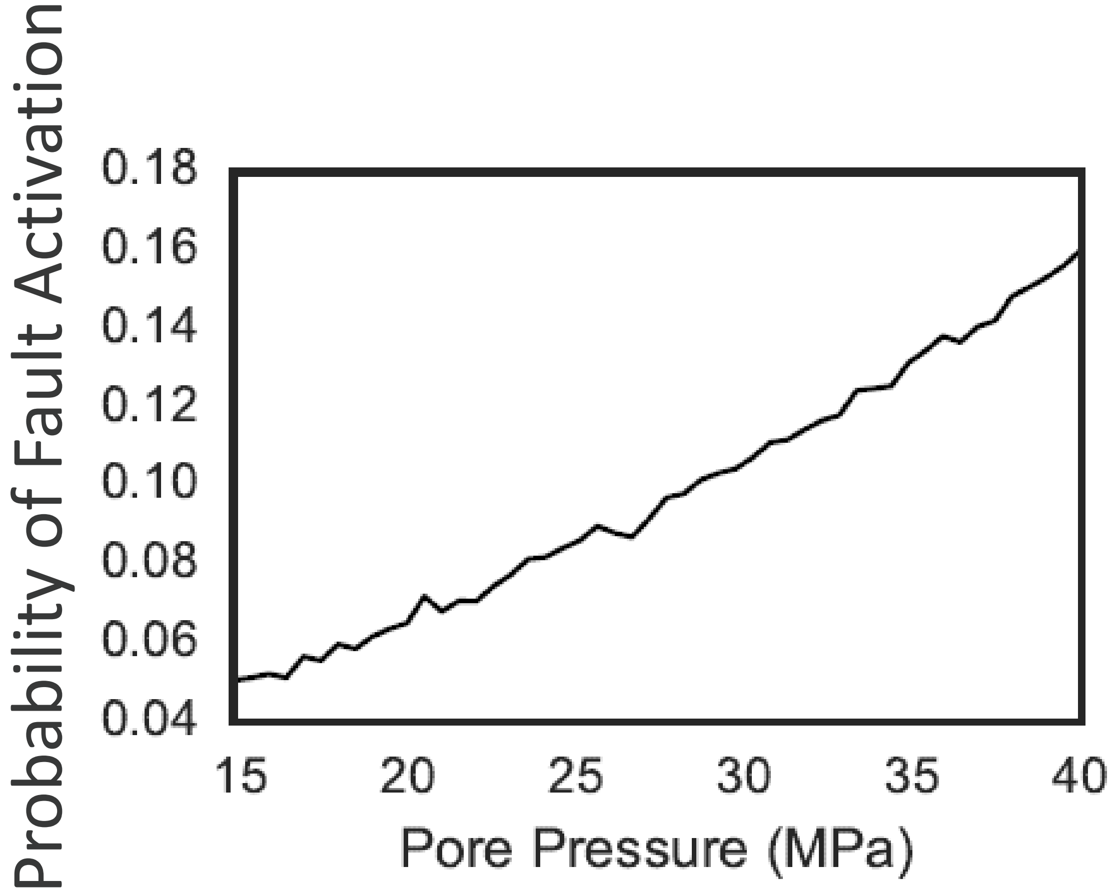
Change in Terzaghi effective stress (used for failure):

$$\Delta\bar{\sigma}_h = \Delta P_p(\gamma_h - 1)$$



Posterior stress distribution after hypothetical stress measurement





Advantages of a Bayesian approach to geomechanics:

- provides more meaningful estimates to other components of a full risk assessment (e.g. fault activation, seal integrity, etc.)
- facilitates value-of-information analyses to make smarter characterization decisions
- more easily integrated into real-time data analysis and decision making

References

White et al, (2016) Induced Seismicity and Carbon Storage: Risk Assessment and Mitigation Strategies. NRAP-TRS-II-005-2016

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